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FEA Study of the MEBT Chopper Target's Bottom Edge

Daryl Oshatz

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August 10, 2000

1.0 Summary

The finite element analysis utilized in the design of the MEBT Chopper Target approximated the incident surface of the faceplate as a flat plane (FE-ME-031, *MEBT Chopper Target Final Design*). This new analysis verifies the accuracy of the flat plane approximation and addresses some of the concerns raised in the Chopper Target Final Design Review on June 20, 2000 (see FE-ME-032). The areas addressed are:

1) The impact of the curved surface on peak stresses.
2) The stress at the brazed interface between the faceplate and backplate near the bottom edge of the target.
3) The stresses resulting from internal water pressure.
4) The stresses which occur in the first few hundred milliseconds of operation (during a cold-start).
5) The effect of decreased convective cooling at the ends of the cooling channels resulting from unanticipated flow stagnation.

None of the effects considered proved significant to the overall design margin reported at the Final Design Review.

2.0 Finite Element Model Description

Only the bottom portion of the target, where the beam hits the TZM Molybdenum faceplate, is included in the model.

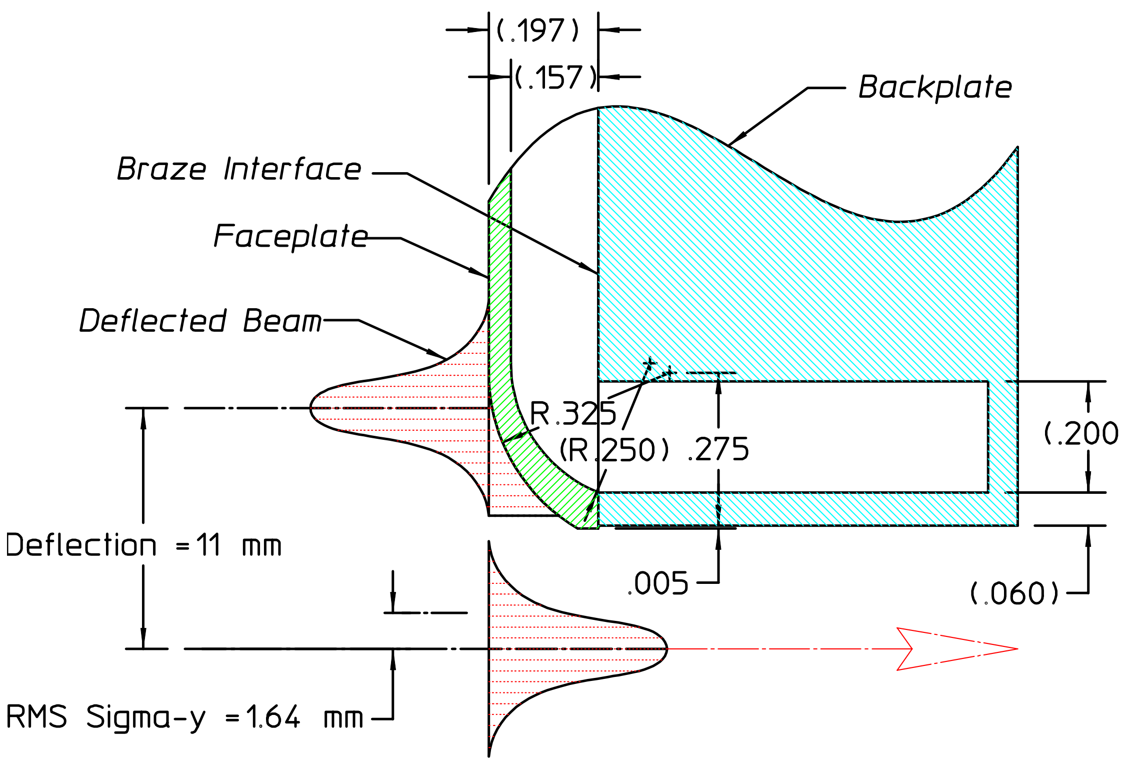

Figure 1 Detailed view of the bottom of the Chopper Target.

The ANSYS 5.5 finite element model consists of 3-D thermal solid (SOLID70) elements,. The x-dimension of the model is 50.8 mm (½ x 4 inches). The factor of ½ is due to vertical symmetry. The y-dimension of the model is just over 20 mm. The overall thickness of the model is 24.13 mm. Except for the vertical (y) dimension, the dimensions of the model match those of the final mechanical design presented at the Chopper Target Final Design Review.

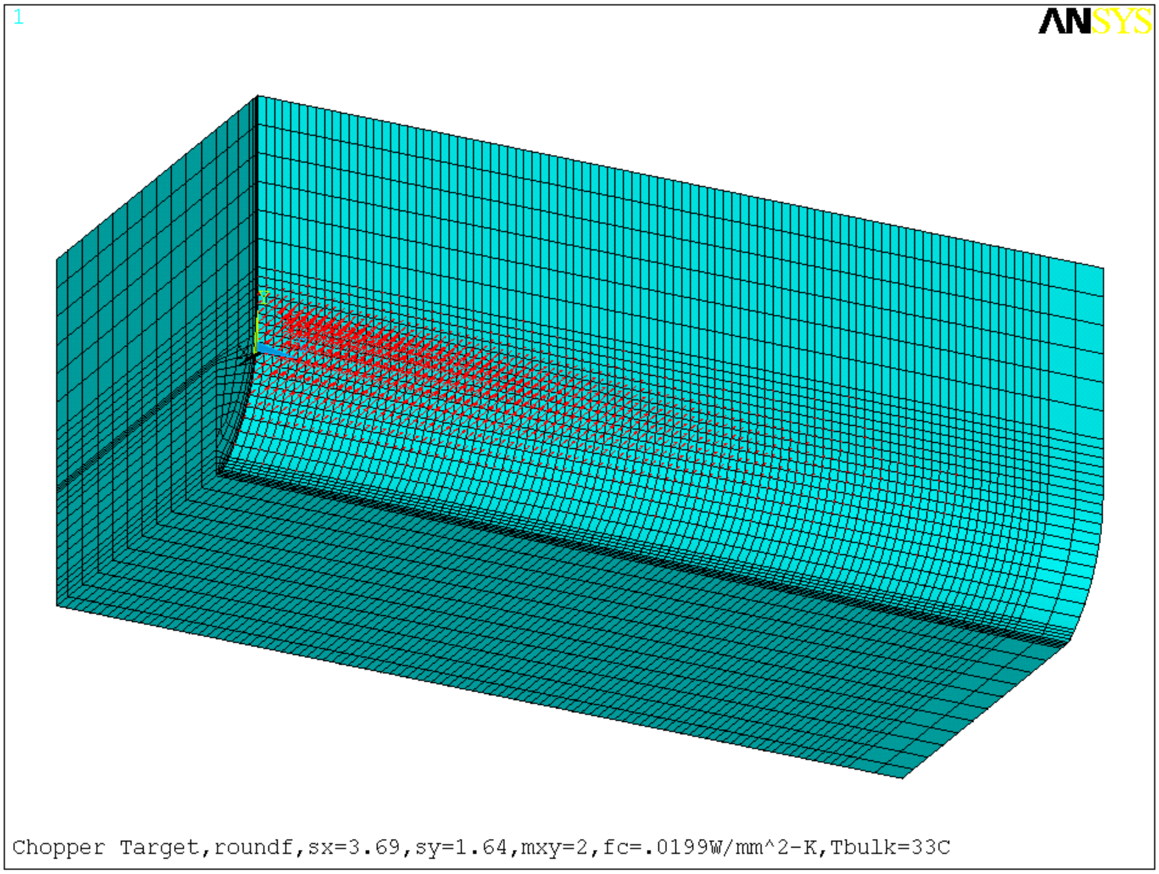

Figure 2 ANSYS FEA Model (48,000 elements, 44,000 active degress of freedom).

Beam power is applied as nodal heat loads according to a bi-gaussian distribution (see input file roundf.inp2) with RMS sigma-x = 3.69 mm and RMS sigma-y = 1.64 mm. The target is tilted such that the normal to the incident surface makes a 75 degree angle with the beam (the projected area is 3.86 times larger than the normal area).

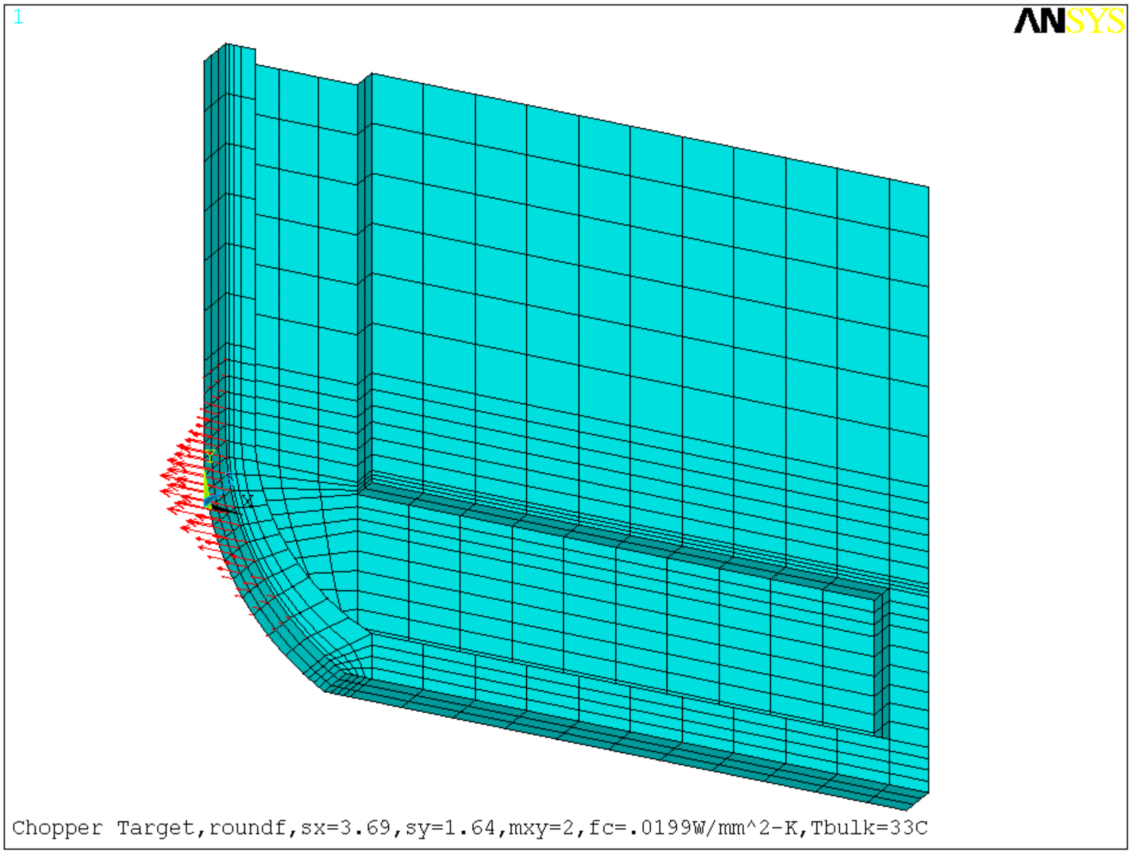

Figure 3 FEA model cross-section showing water cooling passage.

Convective cooling is applied in the water channels (film coefficient = .0199 W/mm^2-K) and plenum (film coefficient = .009 W/mm^2-K). The values used are 25 percent less than those theoretically predicted (Sieder-Tate Equation).

3.0 Results

The thermal transient analysis considers 1.0 millisecond long beam pulses arriving at 60 Hz (every 16.7 millisecond). Triangular pulses, 50 nanoseconds long, peaking at 140 kW, are averaged over one millisecond to form one millisecond long, 8.4 kW pulses.

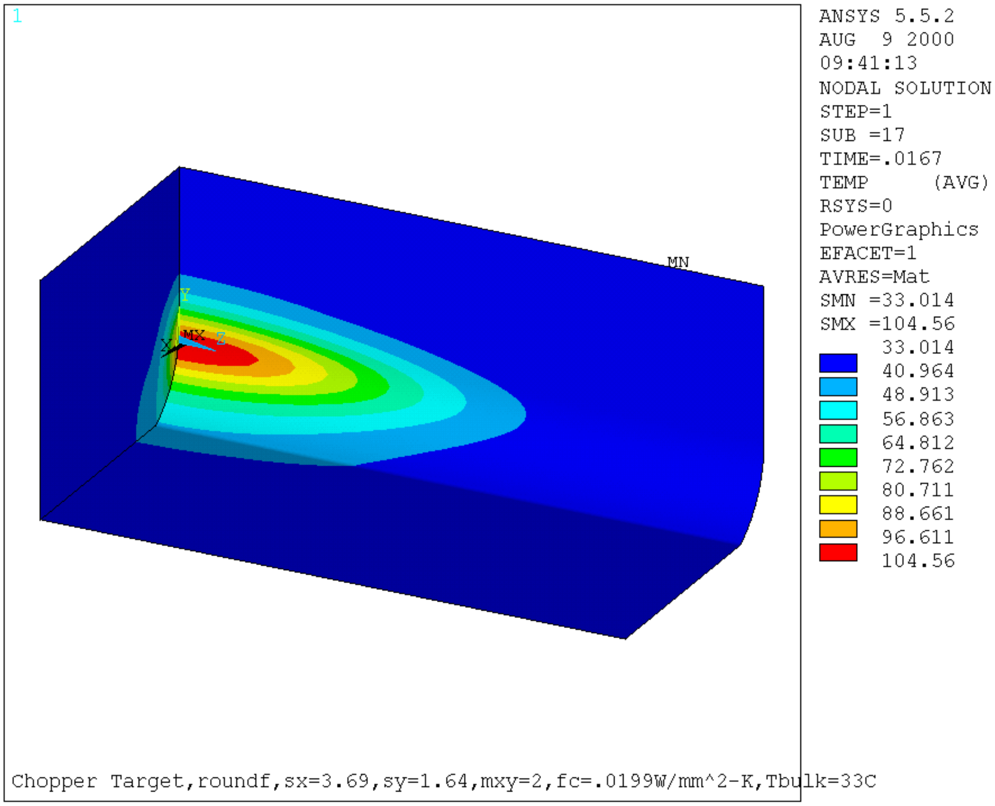

Figure 4 Steady state temperature distribution (504 W average power)

A single-pulse, transient result is obtained by applying a steady state average power of 504 W to the model and then turning transient effects on for a single one millisecond long pulse. This approach was verified and utilized in the previous analysis described in FE-ME-031. The resulting peak temperatures and stresses were shown to be slightly higher using this approximation than when multiple pulses were applied to a transient model. The technique is employed to reduce computing time.

3.1 Flat Plane Approximation

The approximation of the incident surface as a flat plane appears to be valid. A single pulse analysis was performed to compare the results of the curved model to those described in FE-ME-031. The mesh density in the plane of the one millimeter hot wall was much higher in the previous analysis. This model contains four elements across the hotwall thickness while the previous model (FE-ME-031) contained ten elements. The temperatures and stresses vary non-linearly across this one millimeter dimension in the transient analsyis. The longer element edge lengths in this model slightly decrease the predicted temperature and stresses compared to the previous model. This affect is small compared to the uncertainty in the applied load and material properites.

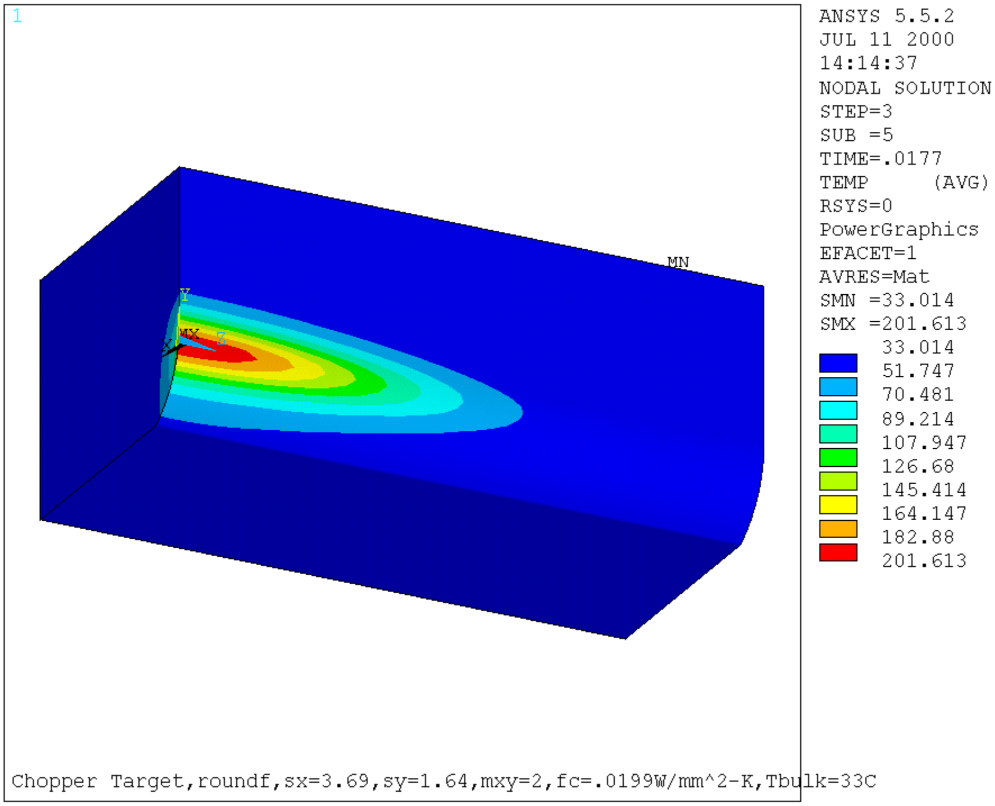

Figure 5 Temperature distribution at the end of a 1 ms 8.4 kW pulse.

The temperature in the center of the beam spot was found to reach 202 °C. The value predicted in FE-ME-031, 206 °C, is approximately two percent higher. The difference in peak temperature is negligible and probably results from the lower mesh density in this model, rather than the curvature of the incident surface.

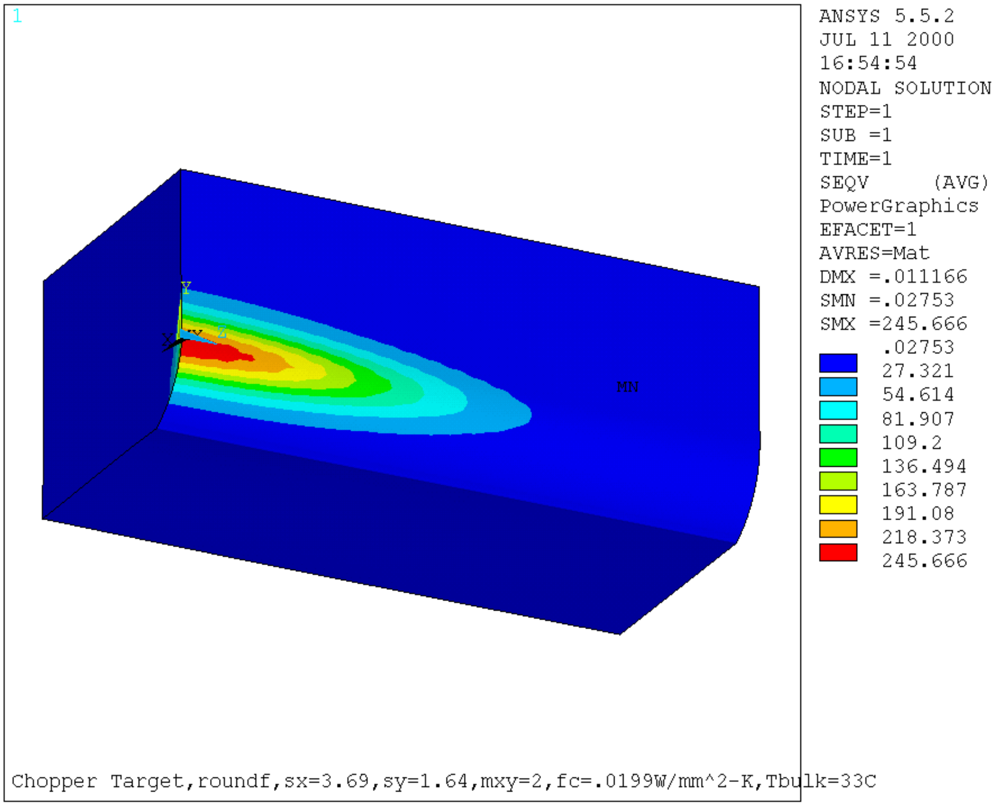

Figure 6 Maximum Von Mises equivalent stress at the end of a one millisecond, 8.4 kW pulse.

The maximum stress occurs at the end of each beam pulse on the front surface of the target. Thermal expansion creates compressive stresses in the plane of the incident surface (the stress component in the vertical direction is approximately two-thirds that in of the direction of the long dimension of the target). The maximum Von Mises equivalent stress value is 246 MPa. This value is nine percent less than the value of 271 MPa predicted in FE-ME-031 and well below the endurance limit for TZM at 200°C of 420 MPa.

3.2 Stress at the Braze Interface

The stresses at the braze interface, resulting from beam induced heating and internal water pressure, were found to be small compared to the anticipate strength of the braze joint, over 400 MPa (see FE-ME-031).

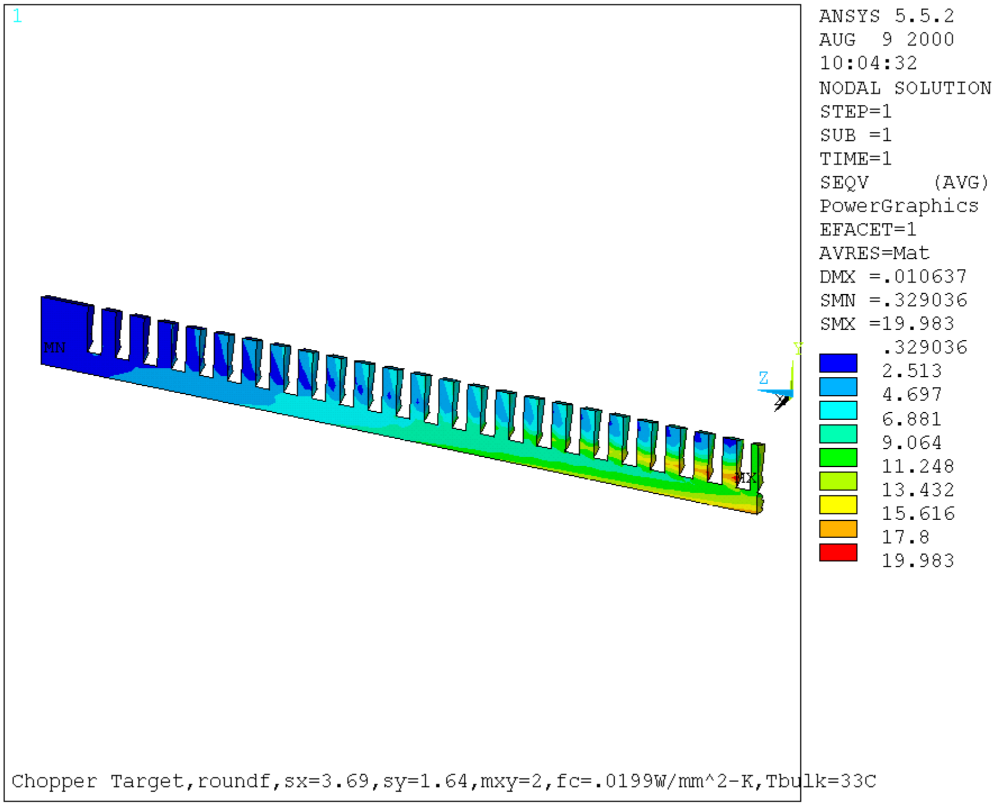

Figure 7 Von Mises equivalent stress at the braze interface resulting from beam induced heating.

The maximum Von Mises equivalent stress in the braze resulting from thermal expansion at the end of a beam pulse was 20 MPa. The maximum Von Mises equivalent stress in the braze resulting from 100 psi of internal cooling water pressure was found to be 37 MPa. Stress in the braze interface will not be a limiting factor for the target design.

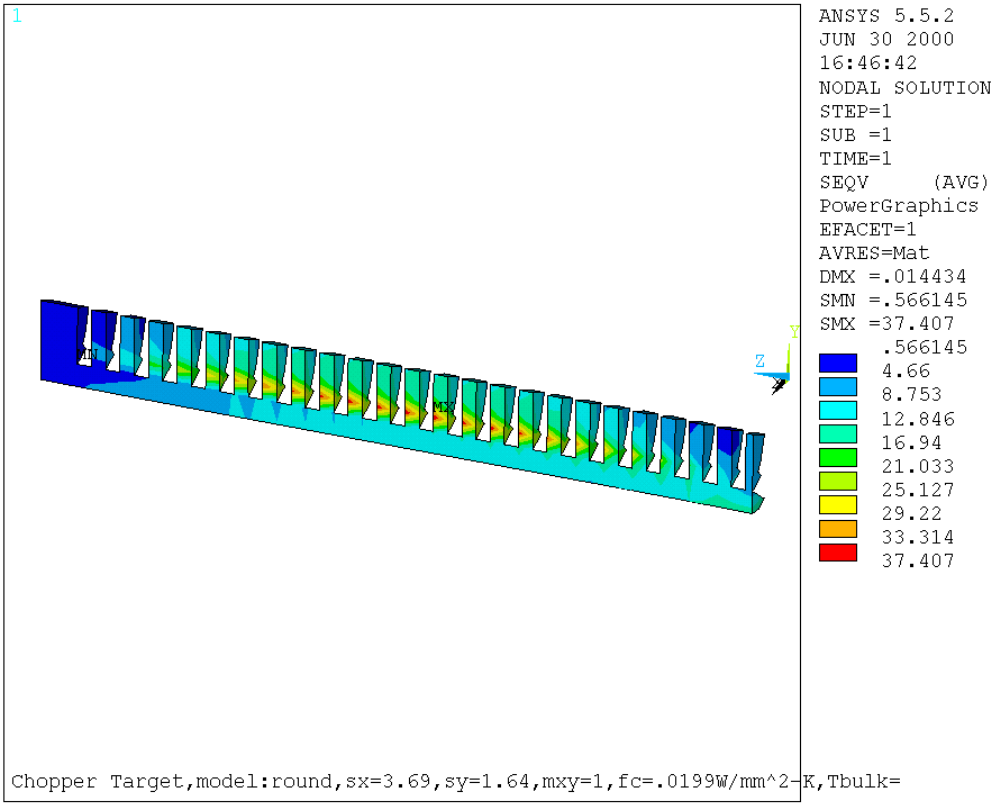

Figure 8 Von Mises equivalent stress at the braze interface resulting from 100 psi of internal water pressure.

3.3 Stress Resulting from Internal Water Pressure

The highest stress resulting from internal water pressure occurs at the braze interface, as discussed above. However, the Von Mises equivalent stress inside the exchange plenum at the back of the target has a value of approximately 36 MPa with 100 psi of water pressure. This stress is extremely small compared to the yield strength of TZM, 655 MPa at room temperature.

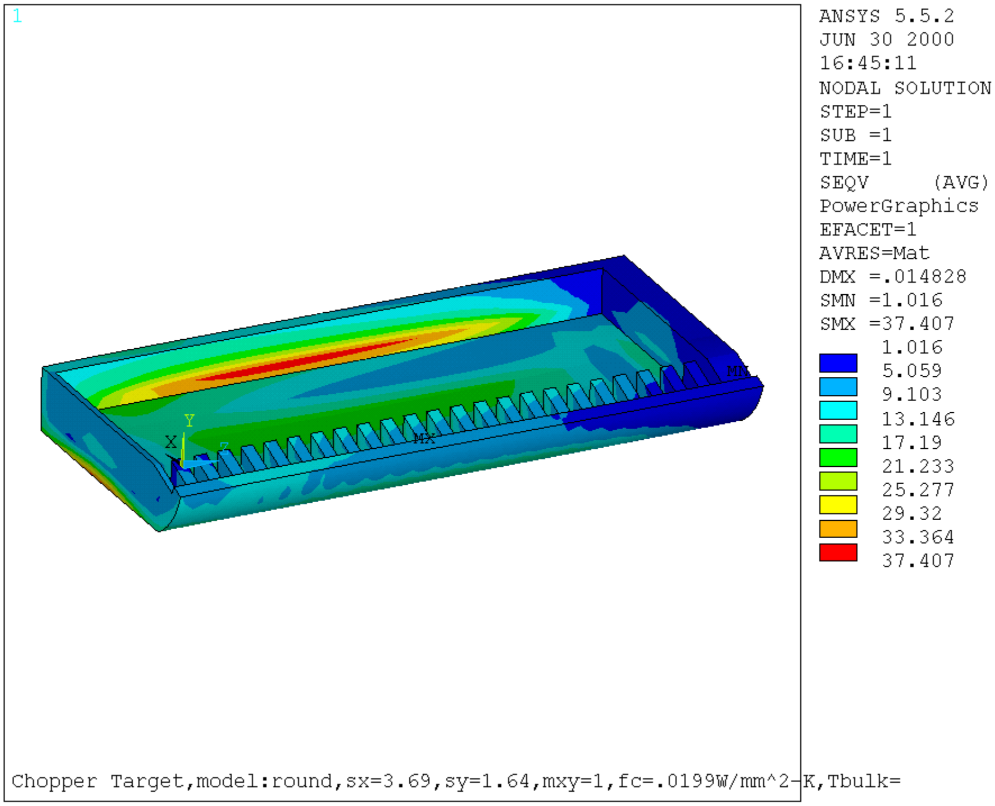

Figure 9 Von Mises equivalent stress in the plenum wall resulting from 100 psi of internal water pressure.

3.4 Cold-Start Transient

Some concerns were raised at the Final Design Review about the possibility that the stresses on the incident surface of the target could be larger during start-up than during continuos operation. A transient analysis was performed to evaluate the surface stresses during start-up. Five consecutive one millisecond pulses were applied to the model, which was initially at the bulk water temperature of 33 °C, at a frequency of 60 Hz.

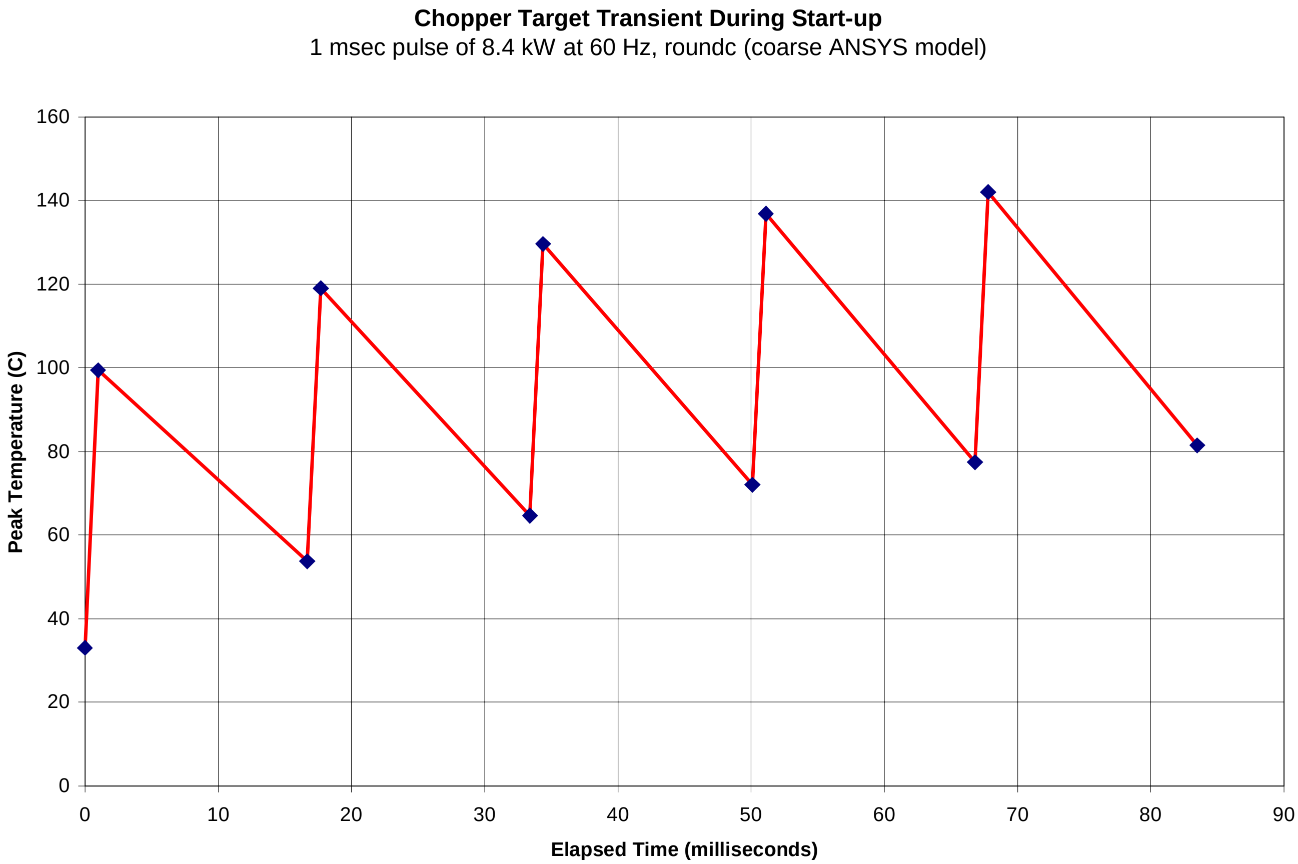

Figure 10 Peak temperature and stress during a simulated cold-start.

The result confirmed that the temperature jumps resulting from individual pulses during start-up are smaller than those occurring as the overall temperature of the target's incident surface rises. The stresses were also found to be lower during start-up than during peak temperature operation.

3.5 Effect of Flow Stagnation in the Ends of the Cooling Channels

Some concern was expressed at the Final Design Review about the possibility that the convective cooling in the ends of the water channels could be less efficient than in the middle of the cooling channels, resulting in a higher peak surface temperature. The reasoning of the previous analysis (FE-ME-031), had been that turbulence in the end of the channels would only increase the effective film coefficient which would lower the peak temperature. However, if flow stagnation were to occur, which is unlikely if both the faceplate and the backplate are machined to proper tolerances and brazed correctly, convective cooling could be locally decreased. This possibility was addressed with a single pulse transient analysis with the film coefficient in the channel ends reduced by fifty percent, from .0199 to .010 W/mm^2-K.

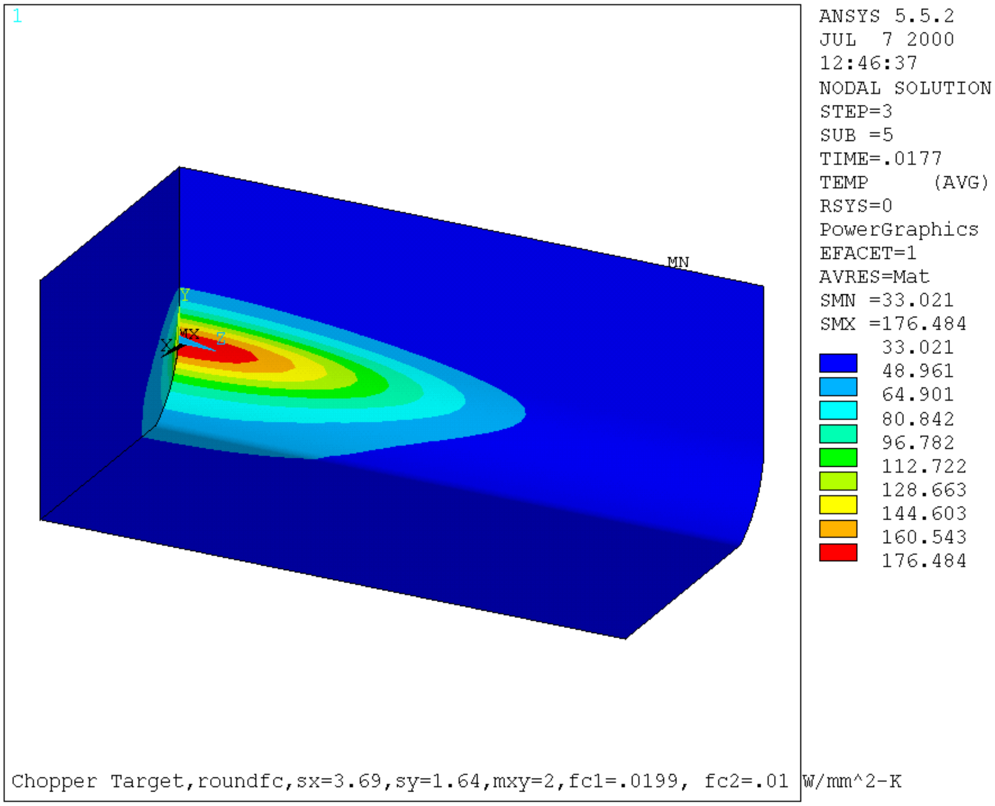

Figure 11 Temperature Distribution with the film coefficient halved in channel-ends.

The model used in this analysis of film coefficient dependency and the cold -start study had a lower mesh density in the hot-wall (two elements across instead of four) which resulted in lower predicted temperatures and stresses than the larger model used in the rest of the cases discussed. This simplification reduced computing time but resulted in 19 percent lower temperatures and 29 percent lower stresses in the smaller model. This smaller model is useful, however, in comparing relative changes.

The peak temperature predicted with the 50 percent reduced film coefficient in the channel ends was 176 °C. Compared to the original value for this coarse model of 164 °C, the peak temperature increased by only seven percent.

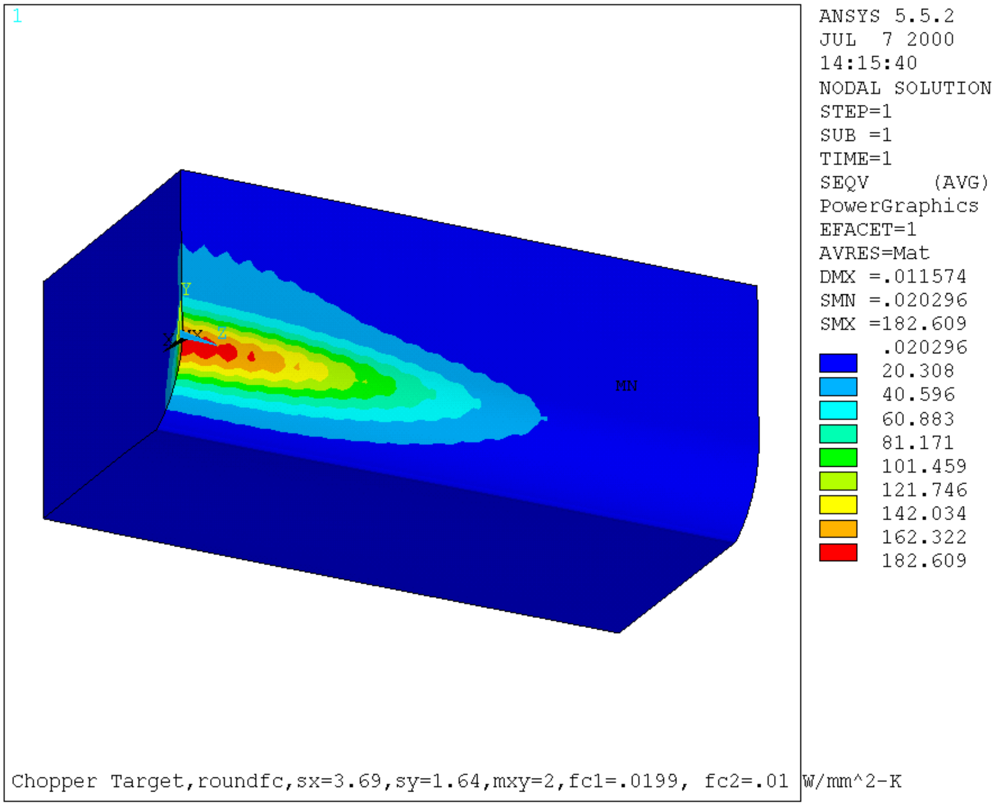

Figure 12 Von Mises equivalent stress with film coefficient halved in channel-ends.

The maximum Von Mises equivalent stress predicted with the 50 percent reduced film coefficient in the channel ends was 183 MPa. Compared to the original value for the coarse model of 174 MPa, the maximum stress increased by only five percent.

A drastic decrease in the convective cooling at the end of the cooling channels, such as the 50 percent decrease considered here, appears to have a small affect on the peak temperature and maximum stress in the faceplate.

4.0 Conclusions

The effect of the curved surface on the bottom of the target and the issues raised in the Chopper Target Final Design Review have been addressed in this analysis. The safety factors reported in FE-ME-031 for the final design are confirmed.

Summary of Results

1) The flat plane approximation used in FE-ME-031 is valid.
2) The stresses at the braze interface at the bottom of the target are less than reported in FE-ME-031.
3) Stresses resulting from internal cooling water pressure are insignificant compared to the strength of the material.
4) Stresses occuring during cold-start operation are less than stresses during continuous operation.
5) Unanticipated flow stagnation at the ends of the channels would not have a significant affect on the overall safety factor of the design.

Appendix

ANSYS 5.5 Input File: roundf.inp

<u>This input file builds the 3-D model and applies thermal boundary conditions</u>

```
/filnam,roundf
/tit,Chopper Target,roundf,sx=3.69,sy=1.64,mxy=2,fc=.0199W/mm^2-K,Tbulk=33C

solv=1          !solv=1 for full solution, solve=0 for build and save model only
sx=3.69         !sigma of beam in x-direction (mm)
sy=1.64         !sigma of beam in y-direction (mm)
hyt=15          !y-location of top of model (above origin) (mm)
hyb=-5.373      !y-locatoin of bottom of model (mm)
w=4*25.4/2      !4" wide target with vertical symmetry (mm)
tw=1            !hotwall thickness (mm)
tf=5            !faceplate thickness (mm)
tp=22.784!dim. to bottom of plenum (mm)
pyt=1.231!y-location of top of plenum (mm)
pyb=-3.849      !y-location of bottom of plenum (mm)
tt=24.13  !total target thickness (mm)
tb=33           !boundary temperature (C)
ro=8.028  !radius of outside of faceplate round (mm)
ri=6.458  !radius of inside of faceplate channel (mm)
mxy=2           !number of divisions per line in x-y plane
tchan=1         !channel and fin thickness (mm) (not adjustable!!)
tangle=3.86     !target 75 degree angle multiplier: 1/cos(75)

/prep7
/view,,-1,-.5,-.5

k,1,tf,hyb
k,2,4.121,hyb
k,3,3.4,-3*sy
k,4,1.684,-2*sy
k,5,.701,-sy
k,6,.169,0
k,7,0,sy
k,8,0,2*sy
k,9,0,3*sy
k,10,0,hyt
k,11,tf,pyb
k,12,2.829,-2.392
k,13,1.860,-1.121
k,14,1.268,.229
k,15,tw,sy
k,16,tw,2*sy
k,17,tw,3*sy
k,18,tw,hyt
k,19,tf,-2
k,20,tf,0
k,21,tf,pyt
k,22,tf,sy
k,23,tf,2*sy
k,24,tf,3*sy
k,25,tf,hyt
k,26,tp,hyb
k,27,tp,pyb
k,28,tp,-2
k,29,tp,0
k,30,tp,pyt
k,31,tp,sy
k,32,tp,2*sy
k,33,tp,3*sy
k,34,tp,hyt
k,35,tt,hyb
k,36,tt,pyb
k,37,tt,-2
k,38,tt,0
k,39,tt,pyt
k,40,tt,sy
```

```
k,41,tt,2*sy
k,42,tt,3*sy
k,43,tt,hyt
k,44,8.028,sy

!draw arcs
larc,3,4,43,ro
larc,4,5,43,ro
larc,5,6,43,ro
larc,6,7,43,ro
larc,11,12,43,ri
larc,12,13,43,ri
larc,13,14,43,ri
larc,14,15,43,ri
lesize,all,,,mxy*1.5

!draw lines
L,1,2,mxy*2
L,2,3,mxy*2
L,1,11,mxy*2
L,3,11,mxy*2,5
L,4,12,mxy*2,5
L,5,13,mxy*2,5
L,6,14,mxy*2,5
L,7,15,mxy*2,5
L,8,16,mxy*2,5
L,9,17,mxy*2,5
L,10,18,mxy*2,5

L,11,19,mxy*1.5
L,19,20,mxy*1.5
L,20,21,mxy*1.5
L,21,22,mxy*1.5
L,22,23,mxy*1.5
L,23,24,mxy*1.5
L,24,25,mxy*3
L,26,27,mxy*2
L,27,28,mxy*1.5
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L,29,30,mxy*1.5
L,30,31,mxy*1.5
L,31,32,mxy*1.5
L,32,33,mxy*1.5
L,33,34,mxy*3
L,35,36,mxy*2
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L,38,39,mxy*1.5
L,39,40,mxy*1.5
L,40,41,mxy*1.5
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L,42,43,mxy*3
L,17,18,mxy*3
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L,18,25,mxy*1.5
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L,11,27,mxy*5
L,19,28,mxy*5
L,20,29,mxy*5
L,21,30,mxy*5
L,22,31,mxy*5
L,23,32,mxy*5
L,24,33,mxy*5
L,25,34,mxy*5
```

```
L,35,26,1
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L,37,28,1
L,38,29,1
L,39,30,1
L,40,31,1
L,41,32,1
L,42,33,1
L,43,34,1
L,7,8,mxy*1.5
L,8,9,mxy*1.5
L,17,16,mxy*1.5
L,16,15,mxy*1.5

!create areas
FLST,2,4,4
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FITEM,2,10
FITEM,2,12
FITEM,2,11
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FLST,2,4,4
FITEM,2,12
FITEM,2,1
FITEM,2,13
FITEM,2,5
AL,P51X
FLST,2,4,4
FITEM,2,13
FITEM,2,2
FITEM,2,14
FITEM,2,6
AL,P51X
FLST,2,4,4
FITEM,2,14
FITEM,2,3
FITEM,2,15
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AL,P51X
FLST,2,4,4
FITEM,2,15
FITEM,2,4
FITEM,2,16
FITEM,2,8
AL,P51X
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FITEM,2,17
FITEM,2,73
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FLST,2,4,4
FITEM,2,18
FITEM,2,44
FITEM,2,19
FITEM,2,43
AL,P51X
FLST,2,3,4
FITEM,2,20
FITEM,2,5
FITEM,2,45
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FLST,2,4,4
FITEM,2,45
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FITEM,2,46
FITEM,2,21
AL,P51X
FLST,2,4,4
FITEM,2,46
FITEM,2,47
FITEM,2,7
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FITEM,2,8
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FITEM,2,73
FITEM,2,49
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FITEM,2,53
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FITEM,2,27
AL,P51X
FLST,2,4,4
FITEM,2,53
FITEM,2,54
FITEM,2,20
FITEM,2,28
AL,P51X
FLST,2,4,4
FITEM,2,54
FITEM,2,55
FITEM,2,21
FITEM,2,29
AL,P51X
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FITEM,2,56
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FITEM,2,25
FITEM,2,59
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FLST,2,4,4
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FITEM,2,36
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FITEM,2,38
AL,P51X
FLST,2,4,4
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AL,P51X
FLST,2,4,4
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FITEM,2,67
FITEM,2,40
AL,P51X
FLST,2,4,4
FITEM,2,67
FITEM,2,33
FITEM,2,68
FITEM,2,41
AL,P51X
FLST,2,4,4
FITEM,2,68
FITEM,2,34
FITEM,2,42
FITEM,2,69
AL,P51X

!input material data from library file
/inp,moly,inp,E:\FEA\library

mat,1
et,1,55
amesh,all

!Extrude in z-direction
!Draw lines for 24 channels
```

```
k,45,.169,0,.5
*do,cnt,1,47
k,,.169,0,.5+cnt*tchan
l,45+cnt-1,45+cnt,mxy
*enddo
l,6,45,mxy/2
k,93,.169,,w
l,92,93,mxy

!drag volumes (areas along lines)
et,2,70
type,2

FLST,2,31,5,ORDE,2
FITEM,2,1
FITEM,2,-31
FLST,8,49,4
FITEM,8,121
FITEM,8,74
FITEM,8,75
FITEM,8,76
FITEM,8,77
FITEM,8,78
FITEM,8,79
FITEM,8,80
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FITEM,8,82
FITEM,8,83
FITEM,8,84
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FITEM,8,87
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FITEM,8,90
FITEM,8,91
FITEM,8,92
FITEM,8,93
FITEM,8,94
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FITEM,8,101
FITEM,8,102
FITEM,8,103
FITEM,8,104
FITEM,8,105
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FITEM,8,111
FITEM,8,112
FITEM,8,113
FITEM,8,114
FITEM,8,115
FITEM,8,116
FITEM,8,117
FITEM,8,118
FITEM,8,119
FITEM,8,120
FITEM,8,122
VDRAG,P51X, , , , , ,P51X

!delete area elements at z=0
asel,s,loc,z,0
```

```
aclear,all

!delete plenum elements in backplate
vsel,s,loc,x,tf,tp
vsel,r,loc,y,pyb,pyt
vsel,r,loc,z,.5,47.5
vclear,all

!delete channel elements in faceplate
vsel,s,loc,y,0,hyt
local,11,1,ro,sy,0
csys,11
vsel,a,loc,x,0,ro-tw
csys,0
vsel,r,loc,x,tw,tf
cm,channels,volu

*do,cnt,1,24,tchan
cmse,s,channels
vsel,r,loc,z,2*cnt-1.5,2*cnt-.5
vclear,all
*enddo

!!!Apply convective cooling
tbulk=33   !bulk water temp. (C)

cmse,s,channels
aslv
asel,u,loc,y,hyt
asel,u,loc,y,3*sy
asel,u,loc,y,2*sy
asel,u,loc,y,sy
csys,11
asel,u,loc,y,187.7,192
asel,u,loc,y,204,208.5
asel,u,loc,y,221.6,227.3
csys,0
cm,chanarea,area

!Apply convective cooling in channels (straight sections)
fc1=.0199 !film coefficient in straight section of channels (W/mm^2-K)

cmse,s,chanarea
asel,u,loc,y,sy,hyb
cm,chan1,area

*do,cnt,1,24,tchan
cmse,s,chan1
asel,r,loc,z,2*cnt-.5,2*cnt-1.5
nsla,s,1
sf,all,conv,fc1,tbulk  !apply film coefficient fc1 w/ tbulk
!d,all,temp,tbulk
*enddo

!Apply convective cooling in channel ends (round areas)
fc2=.0199 !film coefficient in ends of channels (W/mm^2-K)
cmse,s,chanarea
asel,u,loc,y,sy,hyt
asel,u,loc,x,tf
cm,chan2,area

*do,cnt,1,24,tchan
cmse,s,chan2
asel,r,loc,z,2*cnt-.5,2*cnt-1.5
nsla,s,1
sf,all,conv,fc2,tbulk  !apply film coefficient fc2 w/ tbulk
!d,all,temp,tbulk
*enddo

!Apply convective cooling in plenum
```

```
fc3=.009  !film coefficient in plenum (W/mm^2-K)

asel,s,loc,y,sy
asel,a,loc,y,pyb
asel,r,loc,x,tf,tp
asel,r,loc,z,0,47.5
nsla,s,1
sf,all,conv,fc3,tbulk  !apply film coefficient fc3 w/ tbulk
!d,all,temp,tbulk

asel,s,loc,x,tp
asel,r,loc,y,sy,pyb
asel,r,loc,z,0,47.5
nsla,s,1
sf,all,conv,fc3,tbulk  !apply film coefficient fc3 w/ tbulk
!d,all,temp,tbulk

asel,s,loc,x,tf,tp
asel,r,loc,y,sy,pyb
asel,r,loc,z,47.5
nsla,s,1
sf,all,conv,fc3,tbulk  !apply film coefficient fc3 w/ tbulk
!d,all,temp,tbulk

alls
save
```

ANSYS 5.5 Input File: roundf.inp2

<u>This input file applies beam power to the model (504 W steady state, then 8.4 kW pulse)</u>

```
!write load steps
!roundf.inp2

!select those nodes to which power is applied
pave=504/2                    !average power of the beam in watts (with half symmetry)

/prep7
numc,node                     !compress node numbers

csys,11
asel,s,loc,x,ro
csys,0
asel,a,loc,x,0
asel,r,loc,y,3*sy,-3*sy
asel,r,loc,x,0,tf
asel,r,loc,z,0,6*sx*tangle/2
cm,beamarea,area
nsla,s,1
cm,beamnode,node              !node set name is "beamnode"
*get,nnodes,node,,count       !total number of nodes in set beamnode is "nnodes"
*get,nmax,node,,num,max       !max node number in set beamnode is "nmax"
*get,nmin,node,,num,min       !min node number in set beamnode is "nmin"

norm=.1632                    !normalization factor = integral of f(x,y)

/sol
antype,4,new
tunif,33
tref,33
kbc,1

t=.0167

!Apply average power to bring target to steady state
pf=pave/(norm*nnodes)         !pf = multiplier for bi-gaussian which yields correct total power
cmse,s,beamnode
*do,cnt,nmin,nmax,1
*get,zloc,node,cnt,loc,z
*get,yloc,node,cnt,loc,y
*if,yloc,le,3*sy,then
```

```
            *if,zloc,le,3*sx*tangle,then
                        *if,zloc,eq,0,then
                                    f,cnt,heat,pf/2*exp(-zloc*zloc/(2*sx*sx*tangle*tangle)-yloc*yloc/(2*sy*sy))
                        *else
                                    f,cnt,heat,pf*exp(-zloc*zloc/(2*sx*sx*tangle*tangle)-yloc*yloc/(2*sy*sy))
                        *endif
            !*else
                        !cycle
            *endif
!*else
            !cycle
*endif
*enddo

alls
time,t
timint,off,all
autos,on
lswrite,1

!Apply first 8.4 kW pulse
pf=pave/(norm*nnodes)/.06     !pf = multiplier for bi-gaussian which yields correct total power
cmse,s,beamnode
*do,cnt,nmin,nmax,1
*get,zloc,node,cnt,loc,z
*get,yloc,node,cnt,loc,y
*if,yloc,le,3*sy,then
            *if,zloc,le,3*sx*tangle,then
                        *if,zloc,eq,0,then
                                    f,cnt,heat,pf/2*exp(-zloc*zloc/(2*sx*sx*tangle*tangle)-yloc*yloc/(2*sy*sy))
                        *else
                                    f,cnt,heat,pf*exp(-zloc*zloc/(2*sx*sx*tangle*tangle)-yloc*yloc/(2*sy*sy))
                        *endif
            !*else
                        !cycle
            *endif
!*else
            !cycle
*endif
*enddo

alls

time,t+.0005
deltim,.0001,.00005,.0001
timint,on,all
autos,on
lswrite,2

time,t+.001
deltim,.0001,.000025,.0001
lswrite,3

!Remove bi-gaussian power distribution from nodes
cmse,s,beamnode
fdele,all
alls

time,2*t
deltim,.000025,.000025,.003
lswrite,4
```

ANSYS 5.5 Input File: roundfstress.inp

<u>This input file switches element types and applies BC’s for the mechanical solution.</u>

```
!!!Obtain the mechanical solution from the thermal results
!roundfstress.inp
finish
/filename,roundfstress
/prep7
```

```
etchg,tts
finish
/sol
lsclear,all

nsel,s,loc,z,0
d,all,uz,0              !symmetry about z=0

nsel,s,loc,y,hyt
nsel,r,loc,z,0
nsel,r,loc,x,0
d,all,uy,0              !y-restraint
d,all,ux,0              !x-restraint

nsel,s,loc,y,hyt
nsel,r,loc,z,0
nsel,r,loc,x,tt
d,all,uy,0              !y-restraint

alls

ldread,temp,3,,.0177,,roundf,rth
save
antype,static,new
```

ANSYS 5.5 Input File: moly.inp

This input file contains the material properties used for TZM molybdenum (called by roundf,inp).

```
MPTEMP,1,27,127,202,500,1000                              !Temp. in C

! Material #1: Molybdenum TZM Properties
mpdata,alpx,1,5.08e-6,5.12e-6,5.23e-6,5.37e-6,5.53e-6     !mm/mm/K
mpdata,kxx,1,1,.127,.125,.120,.115,.110                   !W/mm/K
mpdata,c,1,1,272,272,272,275,285                          !J/kg/K
mp,dens,1,10.22e-6                                        !kg/mm^3
mpdata,ex,1,1,284e3,274e3,264e3,236e3,216e3   !310e3      !N/mm^2
mp,nuxy,1,.33

!TZM data from Karditsas, P.J., Baptiste, M-J. Thermal and Structural Properties of Fusion related
!Materials  available at http://www-ferp.ucsd.edu/PROPERTIES/
```